# FIDO Rover System Enhancements for High-Fidelity Mission Simulations

Edward Tunstel, Terry Huntsberger, Ashitey Trebi-Ollennu, Hrand Aghazarian, Michael Garrett, Chris Leger, Brett Kennedy, Eric Baumgartner and Paul Schenker

*Jet Propulsion Laboratory, California Institute of Technology*
*4800 Oak Grove Drive, Pasadena, CA 91109 USA*
{firstname.lastname}@jpl.nasa.gov / http://fido.jpl.nasa.gov

**ABSTRACT**

The FIDO (Field Integrated Design & Operations) rover is an advanced mobility platform and research prototype for future Mars surface missions planned by NASA. It was used in a recent field trial aimed at realistic simulation of the 2003 NASA Mars Exploration Rovers (MER) mission. This paper reports the key system enhancements made to improve the utility of the FIDO rover as a platform for high-fidelity, *physical* simulation of Mars surface missions. We describe the approach taken to improve mission-relevant fidelity of the rover system in support of resource modeling, contingency sequencing, and added rover functionality as proposed for the actual mission. This is followed by a brief overview of autonomy technologies demonstrated in the field trial, infused into the flight mission, and advanced relative to the current mission baseline.

## 1. Introduction

The first autonomous planetary rover, named Sojourner, was deployed on Mars in the summer of 1997 as part of the payload on the NASA Mars Pathfinder lander. Sojourner demonstrated the viability of exploring planetary surfaces using mobile robot technology; its mission was limited to minimal scientific surface exploration confined to an area in close proximity to the lander. In 2003, NASA plans to launch a follow up Mars mission that will use two autonomous rovers to explore distinct regions of the planet's surface. These rovers will have greater mobility and autonomy than Sojourner since they are expected to traverse up to 100 meters each Martian day (*sol*) and to conduct exploration independent of a surface lander.

During the spring of 2001, JPL conducted an extended field trial in the southern Soda Mountains of California's Mojave Desert to physically simulate the mission operations approach planned for one rover of the MER mission. The autonomous vehicle used for the field trial was JPL's FIDO rover, a MER prototype. The FIDO rover and its associated end-to-end field testing infrastructure [12] was used to simulate 20 sols of MER-like operational sequences in a complex geological setting analogous to the Martian surface. A team of mission scientists and engineers collaborated with FIDO robotics technologists to conduct the field trial via satellite at JPL, 180 miles from the desert test site, without prior knowledge of the site location (except for aerial imagery typical of Mars orbital observations). As such, the field trial was conducted as if it were a real Mars mission.

Specific objectives, approach, and results of the field trial are reported in [14]. This paper describes enhancements made to increase the fidelity of the FIDO rover as a platform for realistic physical simulation of MER operations scenarios. In Section 2, we provide a brief overview of the system and discuss salient differences between the FIDO rover and the rovers designed for the MER mission. Enhancements to the rover system are then outlined in Section 3. Section 4 highlights the breadth of technologies and related advancements successfully demonstrated in the field, followed by concluding remarks.

## 2. FIDO Rover Overview and MER Comparison

The JPL FIDO *concept* represents a functional architecture and infrastructure for the development, rapid prototyping, and testing of mobility platforms and advanced robotic technologies. The FIDO rover is but one of several autonomous mobility platforms developed at JPL using the FIDO system architecture [12, 13], and it is the predecessor of similar rovers under development at NASA including the JPL Athena Software Development Model [9] and Rocky 8 rovers, and the NASA Ames K9 [5] rover. In form and function, FIDO is a terrestrial model for the rovers designed to accomplish the objectives of the MER mission (see Fig. 1), and is used for end-to-end mission concept testing and validation via annual terrestrial field trials.

FIDO field trials are conducted like remote science exploration missions using a *semi-autonomous* surface mobility approach. The prefix "semi" connotes remote planning, command-sequencing and visualization of rover activity sequences and related data products by an Earth based science-engineering team, all under extreme time delay and intermittent communication afforded by daily uplink/downlink cycles of deep space networks. In the context of science exploration, the FIDO rover does not actually decide *what* to do or *how* to conduct exploration (yet). Rather, the FIDO rover is equipped with intelligent algorithms and software, supported by advanced robotic hardware, necessary to perform autonomous execution of commanded directives and achievement of specified high-level goals that originate with mission operators. More detailed technical descriptions and specifications of the critical FIDO subsystems, mission operations tools, and capabilities can be found in [1, 2, 4, 11, 12].

### *2.1 FIDO and MER Rovers: Functional Contrasts and Similarities*

The FIDO rover is similar in function and capabilities to the MER rovers, although the MER rovers are about 1.5 times larger in size and 2.5 times as massive. Solar panels and onboard batteries provide power for each vehicle. From a systems-level viewpoint, there are subtle functional differences between the rovers' design and configuration in the areas of mobility and sensing for navigation and control. Both designs employ the JPL 6-wheel rocker-bogie suspension and are compatible with respect to motor control and mobility performance, as well as sensing implementations for visual, inertial, and celestial navigation.

Less subtle differences exist with regard to robotic mechanism designs, the most apparent being the mast, which carries stereo imaging systems for terrain surveys and navigation planning, and an infrared point spectrometer for measuring mineral composition of surface materials from a distance. The FIDO mast arm is deployable to variable heights above the solar panel up to 2 meters above ground at full extent; the MER mast has a fixed height of 1.3 meters above ground after a one-time deployment.

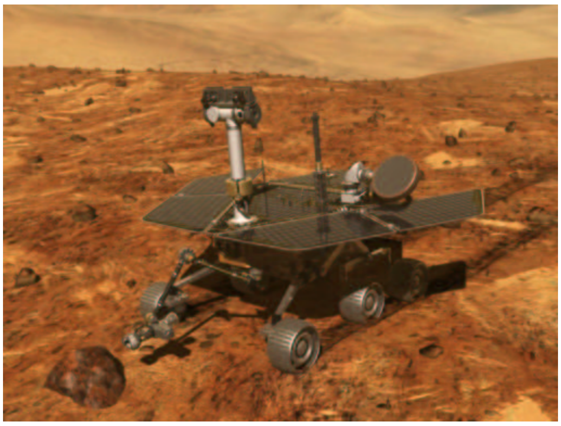

Figure 1. FIDO rover prototype (left) and artist's rendering of MER design (right).

In addition, it is apparent from Fig. 1 that the FIDO mast is located at the rear of the vehicle in contrast to the frontal placement of the MER mast, and that the solar array configurations are very different for the two rover designs. This results in different near-field obscuration patterns (due to the solar panels) for the various mast-mounted instruments. To compensate for some of these differences when simulating MER, the FIDO mast is deployed at the MER mast height during the field tests. Both rover configurations include a robotic arm beneath the frontal area of the solar panel that carries a suite of instruments used for in situ science investigation of surface materials. The FIDO instrument arm carries a color microscopic imager and a spectrometer model for this purpose. The MER instrument arm will carry a microscopic imager, two types of spectrometers, and a tool for abrading rock surfaces.

Relative differences in onboard computing implementations are not significant from the viewpoints of system functionality and remote operations. However, for completeness it is worth noting that significant differences often exist between Earth-based prototypes and rovers bound for space flight. The FIDO onboard computer is a PC/104 266Mhz, Pentium-class CPU running the VxWorks 5.4 real-time operating system. The MER onboard computer will be quite different due to the meager availability of processors that are qualified for space flight (radiation-hardened/tolerant). MER vehicles will carry a 20MHz Rad6000, a radiation-hardened processor, also running VxWorks [9]. The FIDO software is written in ANSI-C and organized as a three-layer architecture. The bottom layer handles low-level hardware device drivers, while the top layer handles application software including motion and instrument command sequences, obstacle avoidance, and path-planning. The middle layer provides the abstraction between higher-level software and the hardware dependencies; it is also responsible for all motion-control functions, stereo vision processing, instrument interfaces, forward and inverse kinematics, etc.

## 3. FIDO Rover System Enhancements

Although important differences in size and instrumentation exist between the FIDO and MER rover designs, the similarities of the two are significant enough to maintain that the same types of challenges exist in commanding FIDO operations in complex terrain on Earth, as are expected for MER on Mars. Be that as it may, additional enhancements to the FIDO rover system were required to improve its fidelity relative to functionality, resource modeling, and operational command sequencing. In this section, we highlight efforts made towards increasing mission relevance and physical simulation fidelity relative to the baseline plan for MER mission operations.

### *3.1 Wheel-Based Soil Excavation*

The FIDO rover is capable of autonomously executing a large variety of robotic activities ranging from instrument pointing and fine-positioning to long-range navigation in complex terrain. In early field test activities [4, 12], its wheels have been used exclusively for mobility. The MER mission scientists desire to use rover wheels for augmented functions related to soil mechanics experiments, as was done previously with Sojourner [10]. As such, it was necessary to implement an approach to use the cleats on the FIDO rover wheels as tools for excavating soil.

Prior to the field trials of spring 2001 the FIDO rover was used to evaluate the feasibility of this approach for exposing near subsurface soil features for observation using its science instruments. Through a series of preliminary tests in hard- and soft-packed soils, techniques for soil *trenching* were evaluated. Trenching was accomplished by rotating the front-left wheel backward while all other wheels maintained fixed positions. After trenching, FIDO backs up to deploy its arm-mounted instruments on the trench and acquire science data. Reverse wheel rotation facilitates backing the rover wheel out of the trench with minimal re-coverage and subsequent disturbance of the excavated soil. Rotating a FIDO rover wheel (20 cm diameter) for six revolutions was sufficient to break through the duricrust of hard-packed soil to depths of 2.5-4.0 cm. In very soft soil, trench depths of one wheel radius could be achieved after three wheel revolutions. A representative soil trench with wheel tracks is shown in the left of Fig. 2 as indicated by the white rectangle. This view is as seen from the frontal body-mounted cameras after driving backward away from the trench. Subsequently, the rover drives forward to deploy the microscopic imager, on the end of its instrument arm, inside the trench as shown in the middle image. The right image of Fig. 2 shows the resulting extreme close-up image of the soil inside the trench.

This preliminary testing revealed a need to improve the strategy for wheel-based trenching as successive trenching attempts would produce wheel motor stall conditions. It was determined that this approach to excavating near sub-surface soil requires constant monitoring and rest periods between short trenching cycles to allow the wheel motor to cool. To achieve this, an improved approach was formulated based on a *progressive trenching* motion sequence. This involves progressive rotation of the wheel through a desired range of motion, interrupted by timed periods of halted motion during which the motor winding was allowed to cool. The sequence of intermediate rotations and cool times was designed based on the motor thermal models to reduce the risk of motor failure. Execution of this sequence results in safer loads during the trenching operation. As a backup, the pre-existing FIDO onboard software provides fault detection and protection against motor stalls, thus mitigating the risk of ultimate motor failure.

This evaluation defined a technical approach and operational baseline for shallow sub-surface trenching followed by remote and in-situ visual analysis. On this basis, soil trenching using a single wheel was elected as a new FIDO rover functionality to be field tested during the MER-FIDO field trial. Additional motor thermal modeling and analysis, supported by motor current monitoring, are required to characterize and further improve the approach.

Figure 2. Left: Soil trench dug using wheel (rover's-eye view); Middle: Placement of the arm-mounted microscopic imager; Right: microscopic image of soil.

### *3.2 Resource Model Development*

The various differences in actual hardware, software, and operations approaches used by the FIDO system versus that planned for the MER mission represent important incompatibilities with regard to resource tracking for rover operations. It was necessary to develop resource models to best account for appropriate mappings between the MER baseline (as known) and FIDO end-to-end systems. To achieve a viable mission simulation, analogue resource models were required for predicting command execution times and associated telemetry data volumes corresponding to a sol's worth of activity sequences. The FIDO onboard power system was upgraded to enable software-controlled power switching of instruments and devices, thus facilitating power monitoring and resource management. However, only modest attention was given to modeling energy utilization for the field trial due to its minimal impact given the test operations timeline — a compressed version of the actual mission operations timeline. The field test timeline allowed for only 2 hours of rover sequence execution per sol simulated. For this duration, it was considered unrealistic for FIDO to consume as much modeled energy as a MER rover would during an actual mission timeline, for which the execution time is about three times longer. From the MER mission operations point of view, the more important issue was to familiarize test participants with the concept of dealing with resource constraints.

The MER mission plan defines several types of Martian sols according to the primary rover activity to take place on a given sol. The categories include sols dedicated to the following activities: panoramic imaging; short (2-10m) and long (>10m) traverses to approach science targets; long drives of at least 80m; remote science using instruments on the mast; and in situ investigations using instruments on the arm. Sequences of rover commands required to autonomously execute each of these sol types were predefined for the MER mission. Based on these MER sol definitions and information about the expected resource utilization by the MER rovers, functionally equivalent FIDO rover sols were defined. Numerous isolated tests were performed with the FIDO rover to record execution times and estimated energy utilization for all relevant FIDO commands/sequences. In addition, models were developed to compute the telemetry data volume associated with FIDO commands (i.e., the expected number of bits of rover state data, images, and/or spectra). This data formed the basis for modeling how long the FIDO system would take to execute equivalent MER sol activities, how much telemetry would be generated and transmitted, and how much energy might be consumed. Overall, 52 resource models were created for FIDO/MER rover command execution. These models were integrated into the mission operations tools with appropriate software modifications for automated downlink processing, uplink planning, and report generation [2]. For each sol, command sequence builders utilized the models to efficiently plan, generate, and verify sets of rover activities that complied with constraints on allotted execution time, available communications bandwidth, and predicted energy budgets over the entire mission.

### *3.3 Contingency Sequencing*

Resource modeling enhancements ensure that feasible command sequences are uplinked to the rover. However, in the inevitable event that autonomous execution of a full sol of activity falters, the rover must be smart enough to fail cognizantly [6]. That is, it must be able to detect failures when they occur. A cognizant failure capability was provided by augmenting the FIDO rover onboard software to support execution of contingency sequences in the event of an unexpected occurrence. Specific engineering and science contingency sequences were defined to be executed in response to failed completion of uplinked commands involving science data acquisition, arm operations, traversal, target approach, and trenching. Engineering contingencies typically return critical rover state information for immediate Direct-to-Earth (DTE) transmission, followed by later transmission of imagery expected to reveal some aspect of the problem via UHF, or orbital relay, communications. Science contingencies are designed to return critical rover state information and remote science data for immediate DTE transmission, while corresponding panoramic imagery is transmitted during the next UHF opportunity.

In each case, detection of a failed command sequence is followed by a contingency sequence that provides the necessary telemetry for mission operators to diagnose the situation, while keeping the rover in a safe mode. Following successful diagnosis, recovery is usually possible via uplink of a corrective sequence of commands. This enhancement not only facilitates ground-based recovery from detected failures, it also allows sequence builders to anticipate potential problems and build-in contingencies that would reduce the risk of losing valuable science data or endangering the rover. A richer instantiation of cognizant failure will be implemented on the MER rovers using language constructs and conditional statements for ground-based and onboard sequencing.

## 4. Field-Demonstrated Technology

In this section we briefly highlight some of the robotics technologies recently developed at JPL and demonstrated in the 2001 MER-FIDO field trial. They were fully integrated with the FIDO architecture, verified in prior field tests and in the JPL MarsYard (an outdoor rover test facility), and improved for utilization in the field trial. The following technologies enhanced FIDO rover autonomy and capability, thereby contributing to a successful MER mission simulation. Fig. 3 shows related scenes of field trial activity.

- *Autonomous on-board arm collision avoidance* software was demonstrated for safe instrument arm placement to diagnose potential arm interaction with the rover and the terrain. The algorithm automatically builds a terrain model from stereo range images and requires no human interaction [8]. The algorithm was also used to supplement mission operations tools as a means to efficiently build safe instrument arm sequences.
- *Onboard Extended Kalman Filter (EKF) state estimation* was demonstrated which fuses wheel odometry, CCD-based sun sensor estimates of absolute heading, and full inertial measurement data (rate sensing and attitude) for accurate rover localization. It provided valuable information used by mission operators for localizing the rover within aerial views of the desert test site. Errors of less than 1% of distance traveled have been reported for this technique [3].
- *Long-range autonomous navigation* was demonstrated with onboard hazard detection and avoidance control using a local path planning algorithm called *DriveMaps* [7].

Figure 3. Remote science, autonomous traverse, and in situ science in the field.

Retrospective evaluations of field trial operations and results often reveal functional limitations or the apparent need for investigating alternative technology options. As an example, the current structure and flow of the planned MER mission operations activities imposes a limitation on the minimum number of sols required to approach a specific target and place instrument arm devices onto it. Successful accomplishment of this sequence of activities can take 2-4 sols under the present strategy. After the 2001 field trial, this limitation was addressed by the FIDO team through implementation and field validation of an automatic target approach sequence that can be accomplished using a single high-level command, and in a single sol. The autonomous sequence uses a visual servoing technique to facilitate navigation to the designated science target while tracking the target location using homography transforms; this is followed by placement of the microscopic imager using automatic focusing based on wavelet texture features. Details of the related algorithms are reported in [7] along with additional algorithmic options for key autonomous mission functions such as high-level navigation and path planning for longer traverses, and onboard execution monitoring for fault detection and diagnosis. Information on these developments may also be found at the JPL FIDO web site (http://fido.jpl.nasa.gov).

One of the objectives of the FIDO concept is to infuse advanced technologies into flight system implementations to increase autonomy and capabilities for planned and future missions. The most recent successes in this regard are the infusion of the onboard arm-collision avoidance technique into the MER flight software and the infusion of the operations planning tool [1] into the MER ground data system tool-suite. The FIDO rover localization and motion control technology are also being considered for implementation on the MER mission. In particular, FIDO algorithms and software for EKF-based state estimation and velocity synchronized all-wheel drive (for improved 6-wheel odometry) are undergoing evaluation by the MER flight software team.

Finally, a number of insights and lessons learned resulted from the 2001 field trial experience. Many of them pertain to desirable features and improvements related to the mission operations tools and user interfaces. There were two specific insights pertaining to the FIDO rover system that provide guidance to further increase fidelity relative to MER mission simulation. The first highlighted the utility of an autonomous capability to perform (and react to) onboard checking of science data quality in order to avoid occasional loss of a sol (due to return of poor quality data) or the risk of data loss. The second called for onboard telemetry and memory management. This insight expresses the notion that there should be a method by which the rover can reveal what requested telemetry it *thinks* it has acquired and transmitted, as well as what science data it has stored in onboard memory. Attention to these issues will be paid in the course of future work.

## 5. Summary and Conclusion

This paper described enhancements made to the JPL FIDO rover system to increase its fidelity for realistic physical simulation of the NASA 2003 Mars Exploration Rovers mission. An additional functionality for soil trenching using a rover wheel was described, as well as measures taken to develop resource models and a facility for contingency sequencing. Specific autonomous rover technologies verified in the field were highlighted in addition to technology advances relative to the MER mission baseline.

Realistic physical simulations such as the 2001 MER-FIDO field trials are valuable rehearsals as well as proving grounds for proposed rover mission operations. They provide opportunities to test sequences in realistic settings, train mission personnel on how to use autonomous rovers to conduct remote field-based science, and identify technologies that require additional development and/or evaluation. FIDO field experience to date has shown that these terrestrial system analogues reduce mission risk, providing cost-efficient integrated technology development, testing and evaluation within a flight-relevant environment, with direct flight participation.

**Acknowledgments**
The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors would like to thank all of the people affiliated with the FIDO team for their contributions to this effort. The collaboration and support provided by the Mars Exploration Rovers Project and personnel is gratefully acknowledged, with special regard to John Callas of the MER Science Office at JPL, and the MER Principal Investigators, Steve Squyres of Cornell University and Ray Arvidson of Washington University, St. Louis.

## References

1. Backes, P.G. et al, "Sequence Planning for the FIDO Mars Rover Prototype," submitted to *Journal of Geophysical Research*, January 2001.
2. Backes, P.G. and J.S. Norris "Automated Rover Sequence Report Generation," *IEEE Aerospace Conference*, Big Sky, MT, March 2001.
3. Baumgartner, E.T., H. Aghazarian, and A. Trebi-Ollennu, "Rover Localization Results for the FIDO Rover," *SPIE Photonics East Conference*, October 2001.
4. Baumgartner, E.T., "In-Situ Exploration of Mars Using Rover Systems, *Proceedings of the AIAA Space 2000 Conference*, AIAA Paper No. 2000-5062, Long Beach, CA, September 2000.
5. Bresina, J.L. et al, "K9 Operations in May '00 Dual-Rover Field Experiment," *6th Intl. Symp. on AI, Robotics and Automation in Space*, Montreal Canada, Paper No. AM010, June 2001.
6. Gat, E. and G. Dorais, "Robot Navigation by Conditional Sequencing," *IEEE Intl. Conference on Robotics and Automation*, 1994.
7. Huntsberger, T. et al, "Rover Autonomy for Long Range Navigation and Science Data Acquisition on Planetary Surfaces", submitted to *IEEE Intl. Conference on Robotics and Automation*, Washington, DC, May 2002.
8. Leger, C., "Efficient Sensor/Model Based On-Line Collision Detection for Planetary Manipulators", submitted to *IEEE Intl. Conference on Robotics and Automation*, Washington, DC, May 2002.
9. Maimone, M.W., J. Biesiadecki and J. Morrison, "The Athena SDM Rover: A Testbed for Mars Rover Mobility," *6th Intl. Symp. on AI, Robotics and Automation in Space*, Montreal Canada, Paper No. AM026, June 2001.
10. Moore, H.J. et al, "Soil-like Deposits Observed by Sojourner, the Pathfinder Rover," *Journal of Geophysical Research*, Vol. 104, No. E4, pp. 8729-8746, April 1999.
11. Norris, J.S. et al, "PTEP: The Parallel Telemetry Processor," *IEEE Aerospace Conference*, Big Sky, MT, March 2001.
12. Schenker, P.S. et al, "FIDO: a Field Integrated Design & Operations Rover for Mars Surface Exploration," *6th International Symposium on Artificial Intelligence, Robotics and Automation in Space*, Montreal Canada, Paper No. AM012, June 2001.
13. Schenker P.S. et al, "Planetary Rover Developments Supporting Mars Science, Sample Return and Future Human-Robotic Colonization," *Proc. IEEE 10th Intl. Conference on Advanced Robotics*, Budapest, Hungary, August 2001.
14. Tunstel, E. et al, "FIDO Rover Field Trials as Rehearsal for the 2003 Mars Exploration Rover Mission," submitted to 9th Intl. Symp. on Robotics and Applications, WAC, Orlando, FL June 2002.